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Helicity-Flip Bremsstrahlung and the Measurement of CP-Violating Form Factors in Polarized e^+e^- Collisions

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Abstract

Certain momentum correlations in the production and subsequent decay of heavy fermion pairs in e^+e^- collisions have increased sensitivity to CP-violating electric and "weak" dipole form factors of the fermion in the presence of longitudinal polarization of the e^+e^- beams. However, unless the polarizations of e^+ and e^- are equal and opposite, collinear initial-state radiation accompanied by helicity flip results in a CP-invariant contribution to these and acts as a background, and must be calculated and subtracted in order to isolate the CP-violating contribution due to the dipole form factor. We calculate this background contribution to such correlations, to order α, in $e^+e^- \to \tau^+\tau^-$ and $e^+e^- \to t\bar{t}$. For the anticitipated luminosities at τ-charm factories and SLC, for the τ, and at a future linear collider with centre-of-mass energy of 500 GeV for the top, these backgrounds are smaller than the statistical background and may be safely neglected.

1 Introduction

An interesting avenue that may lead us to new physics is through indirect methods such as the observation of CP violation outside the $K\overline{K}$ (and $B\overline{B}$) systems [1]. For instance, electric-dipole or "weak"-dipole type couplings of quarks and leptons are predicted in the standard model to be too small to be observable in current experiments. They could be looked for through CP-odd observables in the production and decay of these particles. For example, non-zero CP-odd correlations amongst the momenta of certain final-state particles in the production of $\tau^+\tau^-$ [2, 3, 4] (and of $t\bar{t}$ pairs [5, 6]), in e^+e^- collisions, and their subsequent decay would imply non-zero values for CP-violating form factors that describe the coupling of the $\tau^+\tau^-$ (and of the $t\bar{t}$) pair to either or both the photon and the Z. CP-odd correlations have been looked for at the LEP experiments at CERN, and an upper bound has been placed on the weak dipole coupling of $\tau^+\tau^-$ to Z [7]. While predictions exist for a variety of CP-odd correlations for future experiments [2, 5], certain "vector" correlations have been shown to be substantially enhanced when either or both of the incoming beams are longitudinally polarized [3, 4, 6]. It is also found in the case of $e^+e^- \to t\bar{t}$ that CP-violating asymmetries in the angular and energy distributions of leptons arising from t and $\bar{t}$ decay are enhanced in the presence of longitudinal polarization, increasing the overall sensitivity to the measurement of the CP-violating dipole form factors [8].

While the fact that longitudinal beam polarization improves the sensitivity of CP-odd correlations and asymmetries to the underlying CP-violating

couplings recommends the use of polarization for the measurement of these couplings, there is in principle, a problem at linear colliders, where only electrons can be easily polarized. In the case when the e^+ and e^- polarizations are not equal and opposite, the initial state is not CP even, and correlations which are CP odd in the absence of polarization are not necessarily CP odd in the presence of polarization. In such a case, there would be a contribution to the correlation even from the CP-invariant interaction terms. This has to be calculated and subtracted out before the CP-violating parameters can be extracted from experiment.

In practice, this is not a problem at the lowest order in the fine-structure constant α. This is because for e^+e^- annihilation into a virtual γ or Z, the contribution to any final state in the limit of vanishing electron mass m_e comes from a CP-even initial state consisting of opposite-helicity combinations of e^+ and e^-. Thus the correction to the correlations coming from CP-conserving interactions is negligibly small. However, to the next order in α, there is a contribution from states with like-helicity e^+ and e^- because collinear emission of a hard photon from e^+ or e^- can flip its helicity even in the limit $m_e \to 0$ [9]. This correction has to be calculated when e^+ and e^- longitudinal polarizations are not equal and opposite, and subtracted from measured correlations to get the CP-violating component proportional to dipole form factors.

In earlier work [3, 6] on measurement of τ and t dipole form factors in the presence of longitudinal beam polarization, the CP-even correction to cor-

relations was argued to be small. However, no explicit calculation has been carried out. The purpose of this note is to calculate for arbitrary e^+ and e^- polarizations, the order-α CP-invariant contribution, coming from collinear initial-state bremsstrahlung, to certain correlations in $e^+e^- \rightarrow \tau^+\tau^-$ and $e^+e^- \rightarrow t\bar{t}$, whose measurement in experiments with longitudinally polarized beams was advocated earlier [3, 4, 6]. The calculation has been done using the approach of Falk and Sehgal [10], who show that in the limit of vanishing m_e, the helicity-flip bremsstrahlung process may be calculated from the original process by folding it with a universal function $D_{hf} = (\alpha/2\pi)x$, which describes the emitted radiation. Here x is the ratio of the energy of the photon to the beam energy.

The approach we will follow here is to explicitly compute the contribution of the helicity-flip bremsstrahlung to correlations of certain observables of interest, O_1 and O_2, which are constructed out of the momenta of certain final-state particles and are CP odd in the absence of beam polarization. These are sensitive to the real and imaginary parts of the form factors since they are CPT even and odd, respectively, again in the absence of beam polarization. However, since O_1 is T odd, its correlation can get a contribution from a CP-conserving and T-conserving piece of the interaction only if the amplitude has an absorptive part. Thus, helicity-flip bremsstrahlung at the tree level cannot contribute to $\langle O_1 \rangle$. This we find to be borne out by our explicit calculation. The CP-even background to $\langle O_2 \rangle$ however survives.

Our calculations and numerical results are presented for experimental

situations envisaged for high-precision studies of the τ system, for instance at the τ-charm factories (τCF); for the current SLC experiment; and at a future collider (the Next Linear Collider) that would produce $t\bar{t}$ pairs copiously.

The magnitude of these order-α contributions to correlations will decide the accuracy to which electric and weak dipole form factors can be measured from an experimental determination of the correlations. The correlations determined experimentally, with the order-α CP-even correction subtracted, have to be at least as large as the square root of the variance of the observable times $1/\sqrt{N}$, where N is the number of events in the particular final state in question. This would correspond to the one-standard-deviation upper limit that given statistics would permit on the dipole form factors. It will generally be expected that the order-α corrections we calculate here would be small compared to the zero-order square-root-variance. Then, if it continues to be small compared to the square-root-variance times $1/\sqrt{N}$, its effect can be neglected. This happens to be true for all the cases considered here.

Apart from the fact that the corrections are of order α, there are other reasons for them to be small in certain cases. They are small at the lower of the τCF energies due to the subdominant parity-violating contributions from Z exchange and at SLC due to the non-resonant nature of the bremsstrahlung effects. They are significantly larger at the higher of τCF energies and in the $t\bar{t}$ situation since neither of the causes mentioned above hold here.

2 Notation and Formalism

In this section we will primarily be concerned with the reactions

$$e^-(p_e)e^+(p_{\bar{e}}) \to \gamma^*, Z^* \to \tau^+\tau^- \to \bar{\nu}_\tau X_{\bar{A}}(q_{\bar{A}})\nu_\tau X_B(q_B), \tag{1}$$

and

$$e^+e^- \to \gamma^*, Z^* \to t\bar{t} \to W^+bW^-\bar{b}, \tag{2}$$

where in the former case X_A and X_B can be one of several final states arising in τ decay, and the quantities in parentheses denote four-momenta of particles. We concentrate on $A, B = \pi, \rho$ as in Ref.[3, 4], characterized by their resolving power α for the τ polarization by $\alpha_\pi = 1$ and $\alpha_\rho = 0.46$ and since the calculations can be performed analytically. The reaction (2) is characterized by $\alpha_b = (m_t^2 - 2m_W^2)/(m_t^2 + 2m_W^2)$ and by the fact that the detected particle has a mass negligible compared to the parent in contrast to reaction (1). This leads to simple kinematic replacements in our final computations. Now, the CP-odd observables whose correlations are of interest are

$$O_1 \equiv \frac{1}{2}\left(\hat{\mathbf{p}} \cdot (\mathbf{q}_{\bar{B}} \times \mathbf{q}_A) + \hat{\mathbf{p}} \cdot (\mathbf{q}_{\bar{A}} \times \mathbf{q}_B)\right) \tag{3}$$

and

$$O_2 \equiv \frac{1}{2}\left(\hat{\mathbf{p}} \cdot (\mathbf{q}_A + \mathbf{q}_{\bar{B}}) + \hat{\mathbf{p}} \cdot (\mathbf{q}_{\bar{A}} + \mathbf{q}_B)\right), \tag{4}$$

where $p = \frac{1}{2}(p_{\bar{e}} - p_e)$, and $\hat{\mathbf{p}} = \mathbf{p}/|\mathbf{p}|$ for (1). For (2), the same expressions can be used, but with the simplification that the momenta q_A and q_B represent the single momentum, viz., that of the b quark. Similarly, the $q_{\bar{A}}$ and $q_{\bar{B}}$ both correspond to the momentum of $\bar{b}$. The mean values of these due to possible

non-vanishing of CP-violating form factors and the variance due to standard-model interactions for arbitrary e^+ and e^- polarizations have been computed explicitly and in closed form earlier [4, 6]. We will now present a schematic discussion on performing the computation of interest, viz., calculation of $\langle O_{1,2} \rangle$ for arbitrary beam polarizations arising due to helicity-flip collinear initial-state bremsstrahlung.

The polarized differential cross section written in terms of the cross sections for definite helicity combinations of e^+ and e^- is given by

$$\begin{aligned} \mathrm{d}\sigma^P &= \frac{1}{4}\left[\mathrm{d}\sigma_{LL}(1-P_e)(1-P_{\bar{e}}) + \mathrm{d}\sigma_{LR}(1-P_e)(1+P_{\bar{e}}) \right. \\ &\left. + \mathrm{d}\sigma_{RL}(1+P_e)(1-P_{\bar{e}}) + \mathrm{d}\sigma_{RR}(1+P_e)(1+P_{\bar{e}})\right]. \end{aligned} \tag{5}$$

where the first subscript stands for the e^- helicity and the second for that of the e^+. P_e and $P_{\bar{e}}$ denote the degree of polarization of e^- and e^+ respectively. Our convention is that the polarization is positive for each particle when it is right-circularly polarized.

With only standard model couplings and when $m_e/\sqrt{s} \to 0$, the unpolarized cross section receives only the LR and RL contributions. However, the inclusion of helicity-flip bremsstrahlung introduces an $O(\alpha)$ correction to $\mathrm{d}\sigma^P$ through the non-vanishing of the differential cross section from the LL and RR contributions, even in the limit $m_e/\sqrt{s} \to 0$. In particular we have the result for the extra order-α contribution in the equivalent particle approach [10]:

$$\mathrm{d}\hat{\sigma}_{LL}(p_e, p_{\bar{e}}) = \int_{\xi_{\min}}^{1} \mathrm{d}\xi \frac{\alpha}{2\pi}(1-\xi)\left[\mathrm{d}\hat{\sigma}_{RL}(p'_e, p_{\bar{e}}) + \mathrm{d}\hat{\sigma}_{LR}(p_e, p'_{\bar{e}})\right], \tag{6}$$

for the bremsstrahlung corrected reaction

$$e^-_{L(R)} e^+_{L(R)} \to f \bar{f} \gamma,$$

where $(1-\xi)$ is the fraction of the beam momentum carried by the collinear photon, $\xi_{\min} = 4m_f^2/s$, and $\hat{\sigma}$ denotes the cross section for the basic process $e^+e^- \to f\bar{f}$. The two terms in the square bracket on the right-hand side correspond to the cases when the collinear photon is emitted from the e^- and the e^+, respectively, made explicit by the prime on their respective momenta p_e and $p_{\bar{e}}$ to denote a degraded momentum: $p'_{e(\bar{e})} = \xi p_{e(\bar{e})}$.

The corresponding expression for the right-handed helicities is

$$\mathrm{d}\hat{\sigma}_{RR}(p_e, p_{\bar{e}}) = \int_{\xi_{\min}}^{1} \mathrm{d}\xi \frac{\alpha}{2\pi}(1-\xi) \left[\mathrm{d}\hat{\sigma}_{LR}(p'_e, p_{\bar{e}}) + \mathrm{d}\hat{\sigma}_{RL}(p_e, p'_{\bar{e}})\right]. \qquad (7)$$

The other two helicity combinations correspond to CP-invariant initial states, and would give a vanishing expectation value for the CP-odd variables in the absence of CP-violating interactions, and would therefore not contribute to the background we wish to calculate.

In the presence of CP violation the differential cross section receives a contribution proportional to the CP-violating form factors [2] that yields a non-vanishing result for the expectation values $\langle O_1 \rangle$ and $\langle O_2 \rangle$. The task here is to estimate $\langle O_1 \rangle$ and $\langle O_2 \rangle$ in the standard model due to (6) and (7). This requires the expressions for the spin-density matrix χ_{SM} of Ref. [2] for definite helicity combinations of $e^\pm$. We have made the appropriate changes in the quadratic term involving V_e^i and A_e^i and the expression for the differential cross section expressed in eq. (4.3) of Ref. [2]. We then have the expressions

for $d\hat{\sigma}$ with the helicity combinations as they occur on the right-hand side of (6) and (7). The correlations in the polarized case can then be related through these equations to correlations calculated with $\hat{\sigma}_{LR}$ and $\hat{\sigma}_{RL}$.

Our strategy for calculating these correlations has been to relate the observables $O_{1,2}$ by a Lorentz transformation to other observables in the centre-of-mass frame of e^+ and e^- which obtains after one of them has already radiated a collinear photon. This corresponds to either $\mathbf{p'_e} + \mathbf{p_{\bar{e}}} = 0$, or $\mathbf{p_e} + \mathbf{p'_{\bar{e}}} = 0$, as the case may be. In either of these frames, the initial state corresponding to the subprocess $e^+e^- \to f\bar{f}$ with LR or RL helicity combinations is CP even. Hence only CP-even operators can have nonzero expectation values in this frame. It can be seen that in going to this frame from the laboratory frame, O_1 is unchanged, since it contains only momentum components of the observed momenta transverse to the direction of the boost. Since O_1 is CP odd, it follows that its expectation value vanishes. It therefore vanishes in the laboratory frame as well. This is as expected, since O_1 is T odd, and cannot have nonzero expectation value at tree level.

We now discuss the calculation of the order-α component of $\langle O_2 \rangle$. For each term in (4), we can denote without any confusion the momenta of the final state charged particles by $\mathbf{q}_+$ and by $\mathbf{q}_-$ in the τ system and with the understanding that these stand for the momenta of the $\bar{b}$ and b in the t system. We need to compute $\langle O_2 \rangle$ with the simplified definition of $O_2 \equiv \hat{\mathbf{p}} \cdot (\mathbf{q}_+ + \mathbf{q}_-)$ for our present purposes. In calculating the expectation value for general polarization, the contribution of the LL combination of helicities involves,

choosing the $z(3)$ axis along $\hat{\mathbf{p}}$,

$$\begin{aligned} \mathrm{d}\hat{\sigma}_{LL}(p_e, p_{\bar{e}}) O_2 &= \int_{\xi_{\min}}^{1} \mathrm{d}\xi \frac{\alpha}{2\pi}(1-\xi)\,[\mathrm{d}\hat{\sigma}_{RL}(p'_e, p_{\bar{e}}) \\ &\qquad + \mathrm{d}\hat{\sigma}_{LR}(p_e, p'_{\bar{e}})]\,(\mathbf{q}_+ + \mathbf{q}_-)_3. \end{aligned} \tag{8}$$

The first term on the right-hand side becomes, on writing in the frame $\mathbf{p}'_e + \mathbf{p}_{\bar{e}} = 0$,

$$\begin{aligned} & \int \mathrm{d}\sigma_{RL}(p'_e, p_{\bar{e}})(\mathbf{q}_+ + \mathbf{q}_-)_3 \Big|_{\text{lab. frame}} \\ &= \gamma \int \mathrm{d}\sigma_{RL}(p'_e, p_{\bar{e}}) \left[(\mathbf{q}_+ + \mathbf{q}_-)_3 + \beta(q_+^0 + q_-^0)\right]\Big|_{\text{c. m.}} \end{aligned} \tag{9}$$

where γ and β parametrize the Lorentz transformation between the laboratory frame and the centre-of-mass frame of e^+e^- after photon emission, and read

$$\beta = \frac{1-\xi}{1+\xi}, \qquad \gamma = \frac{1+\xi}{2\sqrt{\xi}}. \tag{10}$$

The term on the right-hand side involving the spatial component of momentum vanishes because it is CP odd, as argued in the case of O_1. Hence, we are only left with the energy term. The second term of eq. (8) is computed with the interchange of the roles of e^- and e^+ with the key difference that the photon is now emitted in the direction opposite to the one in the former case. The result is then

$$\mathrm{d}\sigma_{LL} O_2 = \int_{\xi_{\min}}^{1} \left(\frac{\alpha}{2\pi}\right)(1-\xi)\frac{1-\xi}{2\sqrt{\xi}}\,[\mathrm{d}\sigma_{RL}(\hat{s}) + \mathrm{d}\sigma_{LR}(\hat{s})]\,(q_+^0 + q_-^0)\Big|_{\text{c. m.}}. \tag{11}$$

where $\hat{s} = \xi s$.

What remains now is to evaluate the energy correlation in (11) in the c.m. frame, but with s replaced by $\hat{s}$, and put it together with corresponding

expression for the RR helicity combination. Without going in to the details of this straightforward but somewhat lengthy calculation, we state here the result:

$$\begin{aligned}\langle O_2\rangle_{\rm SM} = -\frac{2}{\sigma}(P_e+P_{\bar e})\frac{\alpha}{2\pi}\int_{\xi_{\min}}^1 {\rm d}\xi\,\frac{(1-\xi)^2}{2\sqrt{\xi}}\frac{4}{3\hat x}\sqrt{1-\hat x^2} \\ \sum_{i,j}\frac{\hat s(V_e^iA_e^j+V_e^jA_e^i)}{(\hat s-m_i^2-{\rm i}m_i\Gamma_i)(\hat s-m_j^2-{\rm i}m_j\Gamma_j)} \\ \Big[(E_A^*+E_B^*)\Big(V_f^iV_f^j(1+\frac{1}{2}\hat x^2)+A_f^iA_f^j(1-\hat x^2)\Big) \\ +\frac{1}{3}(\alpha_Aq_A^*+\alpha_Bq_B^*)(A_f^iV_f^j+A_f^jV_f^i)(1-\hat x^2)\Big]\,,\end{aligned} \tag{12}$$

where $\hat x = 2m_f/\sqrt{\hat s}$, m_i and Γ_i are respectively the mass and width of the intermediate vector boson i, and σ is the lowest-order cross section up to a normalization factor:

$$\begin{aligned}\sigma = \frac{4}{3}(1-x^2)^{\frac{1}{2}}\sum_{i,j}\frac{s}{(s-m_i^2+{\rm i}m_i\Gamma_i)(s-m_j^2-{\rm i}m_j\Gamma_j)} \\ \Big\{(V_e^iV_e^j+A_e^iA_e^j)(1-P_eP_{\hat e})+(V_e^iA_e^j+V_e^jA_e^i)(P_{\bar e}-P_e)\Big\} \\ \cdot\left\{V_f^iV_f^j(1+\frac{x^2}{2})+A_f^iA_f^j(1-x^2)\right\},\end{aligned} \tag{13}$$

with $x = 2m_f/\sqrt{s}$. In (12), the asterisks denote the energy and momenta evaluated in the τ or t rest frame in the respective cases. V_e^i, V_f^i are the vector couplings of e and f currents to the boson i, and A_e^i, A_f^i are the corresponding axial vector couplings. The values of these may be found in [2].

Defining the basic integrals over ${\rm d}\xi$ as

$$\begin{aligned}J_n^{ij}(s) = \int_{\xi_{\min}}^1 {\rm d}\xi \\ \cdot{\rm Re}\left[\frac{(1-\xi)^2\sqrt{\xi-x^2}}{(\xi-m_i^2/s+{\rm i}m_i\Gamma_i/s)(\xi-m_j^2/s-{\rm i}m_j\Gamma_j/s)}\right]\left(\sqrt{\xi}\right)^{1-n},\end{aligned} \tag{14}$$

for $n = 0,\ 2$, we express our final result as

$$\begin{aligned}
\langle O_2\rangle_{\rm SM} &= -\frac{(P_e+P_{\bar e})}{\sigma}\Big(\frac{\alpha}{2\pi}\Big)\frac{4}{3xs} \\
&\sum_{i,j}(V_e^i A_e^j + V_e^j A_e^i)\Big[(E_A^* + E_B^*)\Big\{(V_f^i V_f^j + A_f^i A_f^j)J_0^{ij}(s) \\
&+ \Big(\frac{1}{2}V_f^i V_f^j - A_f^i A_f^j\Big)x^2 J_2^{ij}(s)\Big\} \\
&+\frac{1}{3}(\alpha_A q_A^* + \alpha_B q_B^*)(V_f^i A_f^j + V_f^j A_f^i)(J_0^{ij}(s) - x^2 J_2^{ij}(s))\Big]. \qquad (15)
\end{aligned}$$

Note that in the event $P_e = -P_{\bar e}$, which can be achieved at circular colliders to maximize the prospects of detecting CP violation, $\langle O_2\rangle_{\rm SM}$ is zero. The bremsstrahlung effect is primarily due to unequal polarizations and strongly involves parity violating couplings of the gauge bosons to the electron current.

In Ref. [3, 4] the measurement of the CP-violating form factor by constructing a polarization asymmetrized distribution

$$d\sigma^A = d\sigma^P - d\sigma^{-P},$$

has been advocated, where P is the effective polarization given by

$$P = \frac{P_e - P_{\bar e}}{1 - P_e P_{\bar e}}.$$

This is found to enhance the sensitivity of the measurements. Here we find that O_2 receives a standard model contribution which we denote by $\langle O_2\rangle^A_{\rm SM}$. this is obtained very simply from the expression for $\langle O_2\rangle_{\rm SM}$ by rearranging the expression as $N[P_e, P_{\bar e}]/\sigma[P_e, P_{\bar e}]$ and obtaining

$$\langle O_2\rangle^A_{\rm SM} = \frac{N[P_e, P_{\bar e}] - N[-P_e, -P_{\bar e}]}{\sigma[P_e, P_{\bar e}] - \sigma[-P_e, -P_{\bar e}]}, \qquad (16)$$

This is independent of P_e and $P_{\bar e}$, as the polarization dependence cancels out between the numerator and denominator.

3 Numerical Results

We have carried out numerical evaluations of $\langle O_2\rangle_{\rm SM}$ and $\langle O_2\rangle^A_{\rm SM}$ for the energies we have considered in Ref. [4] for different values of P_e setting $P_{\bar{e}} = 0$ since this is relevant for experiments that have been proposed and for the ongoing SLC experiment[3]. We have done the calculations for the $\tau \to \pi\nu_\tau$ and $\rho\nu_\tau$ channels since these have substantial branching ratios and are characterized by significant resolving power given by $\alpha_\pi = 1$ and $\alpha_\rho = 0.46$. We present the results for $\sqrt{s} = 3.67$ GeV, 4.25 GeV, 10.58 GeV and m_Z in Tables 1 and 2. The correlations shown in Table 1, arising because the initial state is not CP even, may be compared with the background arising from statistical fluctuations. The values of $\sqrt{\langle O_2^2\rangle}$ for the above energies range from about 0.7 to about 10 GeV. Thus, with 10^7 τ pairs being produced, the effect of statistical background is dominant, and one can ignore the fact that the initial state is not strictly CP even.

The case with polarization-asymmetrized distributions is somewhat different. While the values of $\sqrt{\langle O_2^2\rangle}$ continue to be very similar to the ones in the case of ordinary distributions, the contribution to the correlation (shown in Table 2) coming from bremsstrahlung effects is much higher now. However, the number of events in the asymmetrized distributions is much less that in the original distributions. Hence the background arising because the e^- and e^+ polarizations are not equal and opposite is again small compared to the statistical background, and can be neglected.

$\langle O_2\rangle_{\rm SM}$ is small at τCF energies since parity violation is not significant

and at SLC since the bremsstrahlung process is non-resonant.

In Ref. [6] the prospects of probing the dipole form factors with O_1 and O_2 were evaluated. Here $m_t = 175$ GeV and for the planned NLC energy of $\sqrt{s} = 500$ GeV, we have computed $\langle O_2 \rangle_{\rm SM}$ for various values of P_e ($P_{\bar{e}} = 0$) according to the procedure described. The results in Table 3 for the bremsstrahlung contributions to the correlations show that they are negligible compared to $\sqrt{\langle O_2^2 \rangle}/\sqrt{N}$ with $\sqrt{\langle O_2^2 \rangle} \approx 64.5$ GeV as found earlier, and $\sqrt{N} \approx 600 - 900$ as expected for an integrated luminosity of 10 fb^{-1}.

4 Conclusions

We have calculated the $O(\alpha)$ effects due to helicity-flip bremsstrahlung in the measurement of CP-violating form factors. By adapting the equivalent particle approach of Falk and Sehgal to include polarization, we compute corrections within this picture to correlations that are enhanced by the introduction of polarization. We have shown that besides direct searches for new physics, in indirect ones such as through measurements of correlations, the bremsstrahlung process plays a potentially significant role. In practice these remain small as compared to the background coming from statistical fluctuations, for the luminosities considered. The effect is small firstly because it arises at order α, and secondly because it depends on parity violation in the e^+e^- couplings to the gauge boson, which is small at low τCF energies where the photon contribution dominates. At SLC, where the Z

resonance dominates the cross section the effect is even smaller, because it is a convolution of the Breit-Wigner resonance form with a bremsstrahlung probability function which is large only away from the peak. At NLC energies, for the luminosities anticipated, the effect would be swamped by the statistical fluctuations.

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Table Captions

Table 1(a): Values of $\langle O_2 \rangle_{\rm SM}$ in GeV for $\pi\pi$, $\pi\rho$ and $\rho\rho$ channels for $\sqrt{s} = 3.67$ GeV for chosen values of P_e ($P_{\bar{e}} = 0$).

Table 1(b): As above for $\sqrt{s} = 4.25$ GeV.

Table 1(c): As above for $\sqrt{s} = 10.58$ GeV.

Table 1(d): As above for $\sqrt{s} = m_Z$.

Table 2: Values of $\langle O_2 \rangle^A_{\rm SM}$ in GeV for the polarization asymmetrized distributions for $\sqrt{s} = 3.67$ GeV, 4.25 GeV, 10.58 GeV and m_Z.

Table 3: Values of $\langle O_2 \rangle_{\rm SM}$ in GeV for the $t\bar{t}$ system at $\sqrt{s} = 500$ GeV for chosen values of P_e ($P_{\bar{e}} = 0$).

P_e	$\pi\pi$	$\pi\rho$	$\rho\rho$
0	0	0	0
-0.62	$-1.0 \cdot 10^{-12}$	$-1.1 \cdot 10^{-12}$	$-1.1 \cdot 10^{-12}$
0.62	$1.0 \cdot 10^{-12}$	$1.1 \cdot 10^{-12}$	$1.1 \cdot 10^{-12}$
-0.75	$-1.2 \cdot 10^{-12}$	$-1.3 \cdot 10^{-12}$	$-1.4 \cdot 10^{-12}$
0.75	$1.2 \cdot 10^{-12}$	$1.3 \cdot 10^{-12}$	$1.4 \cdot 10^{-12}$
-1.00	$-1.6 \cdot 10^{-12}$	$-1.7 \cdot 10^{-12}$	$-1.8 \cdot 10^{-12}$
1.00	$1.6 \cdot 10^{-12}$	$1.7 \cdot 10^{-12}$	$1.8 \cdot 10^{-12}$

Table 1(a)

P_e	$\pi\pi$	$\pi\rho$	$\rho\rho$
0	0	0	0
-0.62	$-6.5 \cdot 10^{-10}$	$-6.5 \cdot 10^{-10}$	$-6.4 \cdot 10^{-10}$
0.62	$6.5 \cdot 10^{-10}$	$6.5 \cdot 10^{-10}$	$6.4 \cdot 10^{-10}$
-0.75	$-7.9 \cdot 10^{-10}$	$-7.8 \cdot 10^{-10}$	$-7.7 \cdot 10^{-10}$
0.75	$7.9 \cdot 10^{-10}$	$7.8 \cdot 10^{-10}$	$7.7 \cdot 10^{-10}$
-1.00	$-1.1 \cdot 10^{-10}$	$-1.0 \cdot 10^{-10}$	$-1.0 \cdot 10^{-10}$
1.00	$1.1 \cdot 10^{-10}$	$1.0 \cdot 10^{-10}$	$1.0 \cdot 10^{-10}$

Table 1(b)

P_e	$\pi\pi$	$\pi\rho$	$\rho\rho$
0	0	0	0
-0.61	$-1.7 \cdot 10^{-6}$	$-1.4 \cdot 10^{-6}$	$-1.1 \cdot 10^{-6}$
0.61	$1.7 \cdot 10^{-6}$	$1.4 \cdot 10^{-6}$	$1.1 \cdot 10^{-6}$
-0.75	$-2.1 \cdot 10^{-6}$	$-1.7 \cdot 10^{-6}$	$-1.3 \cdot 10^{-6}$
0.75	$2.1 \cdot 10^{-6}$	$1.7 \cdot 10^{-6}$	$1.3 \cdot 10^{-6}$
-1.00	$-2.8 \cdot 10^{-6}$	$-2.3 \cdot 10^{-6}$	$-1.8 \cdot 10^{-6}$
1.00	$2.8 \cdot 10^{-6}$	$2.3 \cdot 10^{-6}$	$1.8 \cdot 10^{-6}$

Table 1(c)

P_e	$\pi\pi$	$\pi\rho$	$\rho\rho$
0	0	0	0
-0.62	$-2.3 \cdot 10^{-5}$	$-1.7 \cdot 10^{-5}$	$-1.1 \cdot 10^{-5}$
0.62	$2.8 \cdot 10^{-5}$	$2.1 \cdot 10^{-5}$	$1.4 \cdot 10^{-5}$
-0.75	$-2.1 \cdot 10^{-5}$	$-2.0 \cdot 10^{-5}$	$-1.4 \cdot 10^{-5}$
0.75	$3.4 \cdot 10^{-5}$	$2.6 \cdot 10^{-5}$	$1.7 \cdot 10^{-5}$
-1.00	$-3.5 \cdot 10^{-5}$	$-2.6 \cdot 10^{-5}$	$-1.7 \cdot 10^{-5}$
1.00	$4.8 \cdot 10^{-5}$	$3.6 \cdot 10^{-5}$	$2.4 \cdot 10^{-5}$

Table 1(d)

$\sqrt{s}$	$\pi\pi$	$\pi\rho$	$\rho\rho$
3.67	$1.8 \cdot 10^{-8}$	$1.9 \cdot 10^{-8}$	$2.0 \cdot 10^{-8}$
4.25	$8.8 \cdot 10^{-6}$	$8.7 \cdot 10^{-6}$	$8.6 \cdot 10^{-6}$
10.58	$3.7 \cdot 10^{-3}$	$3.0 \cdot 10^{-3}$	$2.3 \cdot 10^{-3}$
m_Z	$-2.6 \cdot 10^{-4}$	$-1.9 \cdot 10^{-4}$	$-1.3 \cdot 10^{-4}$

Table 2

P_e	$\langle O_2 \rangle_{\rm SM}$
-0.62	$1.5 \cdot 10^{-3}$
0.62	$-2.4 \cdot 10^{-3}$
-0.75	$1.7 \cdot 10^{-3}$
0.75	$-2.9 \cdot 10^{-3}$
-1.00	$2.2 \cdot 10^{-3}$
1.00	$-4.8 \cdot 10^{-3}$

Table 3